Intersecting Brane Models and Cosmology

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Abstract. We discuss the application of general features of intersecting brane model constructions in cosmology. In particular, we describe a scenario for D-term inflation which arises straightforwardly in IBM constructions wherein open non-vectorlike strings play the role of the inflaton. We also show that baryogenesis driven by hidden sector mixed anomalies can naturally arise in intersecting brane models.

1 Introduction

There have been several attempts to use string theory to make connections between quantum gravity and the physics which can be observed at low-energies. Cosmology has been one particular focus of attention [1]. In recent years, intersecting brane models (IBMs) in Type II string theory have been one well-studied scenario[2]. In this scenario, gravitational physics is generated as usual by closed strings, while the open strings stretching between D-branes generate the gauge and matter degrees of freedom of the Standard Model.

Several explicit intersecting brane models have been constructed, but it seems clear from the nature of the constructions that known examples are merely the simplest. Moreover, this very simplicity has been somewhat counterproductive, as each of the known models fails in some way to match low-energy observations. Indeed, the very large number of possible IBMs suggests that any particular explicit construction likely does not describe the real world in detail. As such, any lesson which is particular to a specific construction may be irrelevant to more realistic models.

In this work we emphasize a different approach, which is to focus on general new features which are common to a wide class of IBMs. The advantage of such an approach is that, although new physics may be illustrated in a specific simple example, the results can be exported to more complicated models which are also more realistic.

In section 2 we describe the general features of intersecting brane models which are relevant for the new physics which we discuss. In section 3 we describe a scenario of D-term inflation which arises naturally in this IBM setup. In section 4 we describe a mechanism for baryogenesis which also arises naturally in IBMs, and we conclude with a discussion of future prospects in section 5.

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2 Intersecting Brane Models

Type II string theory naturally lives in 10 dimensions. In an IBM, one compactifies this space on 6D orientifolded CY 3-fold. This reduces the supersymmetry of the theory from 32 real supersymmetries to the more realistic $N = 1$ SUSY in 4D. The spacetime-filling orientifold planes introduced by the compactification are charged; Gauss' Law (equivalently, the RR-tadpole constraints) requires that this charge be cancelled, and one can do so by introducing D6-branes (in Type IIA) which fill spacetime and wrap appropriate 3-cycles of the compactification manifold. These branes provide an extra feature - the open strings which begin and end on these branes generate a gauge theory, as well as chiral matter. For a realistic IBM, we would like one sector of this gauge theory to be SM-like. But generally we will have additional sectors, since there is no reason for the branes which provide the SM gauge theory alone to be precisely sufficient to cancel all tadpoles.

In these models, the gauge bosons arise from strings beginning and ending on the same brane, and the gauge group is determined by the number of branes which are stacked on top of each other ($U(N)$ for branes which do not lie on orientifold planes). Chiral matter arises from open strings which stretch from one brane stack to another (or its orientifold image), and transforms under the bifundamental representation of the two gauge groups associated with the two brane stacks. The number of such multiplets in each representation is counted by the topological intersection number of the brane stacks.

It is important to note that any two brane stacks will generally have a non-zero intersection number. This is true because any two 3-cycles will generically intersect on a 6-manifold. This implies that for two gauge groups $U(N_a)$ and $U(N_b)$, there generically exists non-vectorlike matter transforming in the bifundamental representation. This in turn will contribute

to a mixed anomaly of the form $[U(1)_a U(N_b)^2]$, where $U(1)_a$ is the diagonal subgroup of $U(N_a)$. Note that although we have specifically focussed on IBMs in the context of Type IIA string theory, similar statements follow for T-dual models in Type IIB.

This analysis provides us with the two lessons regarding IBMs which we will use, namely, the generic appearance of hidden sector gauge groups with matter in the bifundamental representation, and the generic appearance of $U(1)$ mixed anomalies which are fixed by the Green-Schwarz mechanism.

3 D-term Inflation

Suppose we have N brane stacks in the hidden sector. From the preceding discussion, we see that the diagonal subgroups living on each stack will provide N D-term equations, while we expect to have $\mathcal{O}(N^2)$ scalars arising from the strings stretching between these branes. The first corollary of our above general features is that there will be many D-flat directions. We plan to use this feature to provide for a flat inflaton potential.

Basically, we can summarize the plan as follows

- First, separate off a term V_{inf}^D from the remaining D-terms V_{rest}^D. Schematically, we have $V_{\text{inf}}^D = \frac{g^2}{2}(|\phi_+|^2 - |\phi_-|^2 - \xi)^2$, where ϕ_+ is the waterfall field which ends inflation.
- Move out along a flat direction of V^D.
- A generic Yukawa coupling of the form $W = \lambda S \phi_+ \phi_-$ will generate a potential for the waterfall field of the form $V_F = \lambda^2 |S^2||\phi_+|^2 + \dots$. If S gets a vev when moving out on the D-flat direction, this mass will lift the waterfall field and allow inflation to proceed as normal in D-term inflation.
- A 1-loop Coleman-Weinberg potential of the form $V = V_0(1 + \frac{g^2}{4\pi^2} \log \frac{\lambda^2 S^2}{\Lambda^2})$ will cause the inflaton S to slowly roll back. When it reaches a critical value, the waterfall field becomes tachyonic and inflation ends.
- The extra gauge symmetry keeps the inflaton direction flat by suppressing superpotential corrections.

This plan follows the standard form for generating D-term inflation[3]; we see how this plan can be realized in the IBM setup[4]. One point to note is that in the standard D-term inflation picture, one must always make sure that the inflaton direction is flat. We have chosen a D-flat direction for the inflaton, but one must be sure that superpotential terms do not lift this flat direction (for example, a term of the form $W = mS^2$ could lift one out of the slow-roll regime). In typical field theory models, one usually relies on R-symmetry to ensure that such tree-level mass terms are projected out. One cannot necessarily guarantee that the right discrete symmetry exists in any specific model, though. In our IBM setup, we see that the extra gauge invariance of the hidden sector saves us. Gauge invariance prevents the existence of a large tree-level mass for the inflaton. And as usual for D-term inflation, Kähler
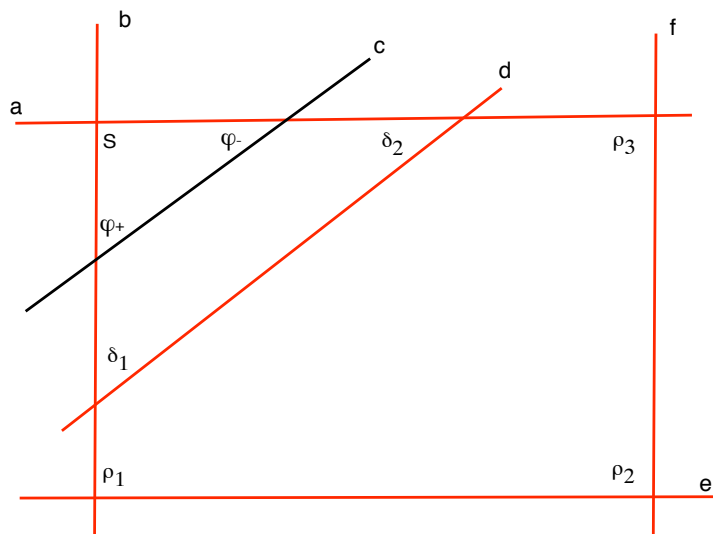

Fig. 1. This shows a setup of intersecting branes in type IIA that can yield D-term inflation. We have a total of 6 branes. Brane c is our inflationary brane. Branes a and b give rises to the necessary Yukawa coupling between the inflaton and the waterfall field. Branes e and f are there to ensure that the D-term potential has a flat direction. This flat direction is broken by the F-term potential but this is planckian suppressed. Finally, brane d is necessary for the anomalies to cancel, it plays no other role during the inflationary era. S, $\phi_\pm$, $\delta_{1,2}$ and $\rho_{1,2,3}$ are the various bifundamental fields at each intersections. Also note that this picture is a two dimensional depiction of a configuration that actually lives in six curved dimensions.

corrections to the F-term potential are small because $V_F \ll V_D$.

Furthermore, the D-flat direction which is used for the inflaton must involve turning on more than one field. One can see this simply by noting that each field is charged under two gauge groups, and thus contributes to two D-terms. Turning on such a field alone cannot be a flat direction. Instead, the fields which are turned on must form an oriented polygon in the associated quiver diagram (i.e., for each $U(1)$ factor we must turn on two fields which are oppositely charged). In this way, the positive contribution to any D-term by one scalar field is compensated by the negative contribution by the next scalar.

The diagram in fig. 1 is illustrative. This is a schematic example of an IBM hidden sector which can exhibit D-term inflation. As will be clear, the details of this model are not essential to the construction; many other models will work equally well. In this example, the brane c is the inflationary brane, yielding

$$
\begin{aligned}
V_{\text{inf}}^D &= g_c^2(|\phi_+|^2 - |\phi_-|^2 - \xi_c)^2 \,, \\
V_{\text{rest}}^D &= g_a^2(|\phi_-|^2 - |S|^2 + |\rho_3|^2 - \xi_a)^2 \\
&\quad + g_b^2(|S|^2 - |\phi_+|^2 - |\rho_1|^2 - \xi_b)^2 \\
&\quad + g_e^2(|\rho_1|^2 - |\rho_2|^2 - \xi_e)^2 \\
&\quad + g_f^2(|\rho_2|^2 - |\rho_3|^2 - \xi_f)^2 \,.
\end{aligned}
$$

For simplicity, we have chosen $\xi_d = \delta_1 = \delta_2 = 0$. The waterfall field ϕ_+ gets a tachyonic $mass^2$ from V_{inf},

and inflation ends when it condenses. The inflaton is the flat direction which arises from turning on the four fields S and $\rho_{1,2,3}$ living at the corners of the "square."

A worldsheet instanton arises from a string worldsheet stretching along the triangle bounded by the a, b and c branes. This instanton generates the Yukawa coupling $W = \lambda S \phi_1 \phi_2$. When S gets a vev, the potential term

$$V_F = \lambda^2 (|S|^2 |\phi_+|^2 + |S|^2 |\phi_-|^2 + |\phi_+|^2 |\phi_-|^2)$$

lifts the $mass^2$ of the waterfall field, making it non-tachyonic. But the one-loop Coleman-Weinberg potential $V = V_0(1 + \frac{g^2}{4\pi^2} \log \frac{\lambda^2 S^2}{\Lambda^2})$ causes S to roll back along the D-flat direction until the waterfall field becomes tachyonic, ending inflation.

The only Yukawa coupling which could lift the D-flat direction is of the form

$$W = \frac{\lambda'}{M_p} S \rho_1 \rho_2 \rho_3,$$

which is M_p-suppressed. The polygon formed by the branes whose intersections yield the inflaton flat direction could have more than four sides. A larger polygon would result in more M_p factors in the Yukawa coupling denominator, and greater suppression of the F-terms which might lift the inflaton direction. For this simple "square" example, as is often the case in inflationary models, M_p suppression is not necessarily enough. To stay in the slow-roll regime one must have $g^2 \lambda^2 \leq 10^{-13}$.

Since λ is generated by a worldsheet instanton and is thus exponentially suppressed, this tuning might not be unreasonable. But in any case, this arises only in this simple example; for a slightly more complicated example where the flat direction comes from a "pentagon" or larger polygon, the fine-tuning is much less severe. Thus we see one of the advantages of this IBM setup; *the numerical fine-tuning of the curvature of the potential is replaced by a discrete fine-tuning of the sign of brane intersection numbers.*

The observational constraints from cosmology are the correct size of density perturbations ($P_{\mathcal{R}} \sim 10^{-9}$) and the spectral index ($n_s \sim 1$), and that there be at least 60 efolds of inflation. In this setup, for moderate-sized Yukawa couplings one finds the standard D-term inflation prediction of a slightly red spectrum, $n_s \sim 0.98$. This value is not optimal, yet not inconsistent with the latest WMAP data [5]. In this regime one has $\xi \sim 10^{-5} M_p^2$, which gives us a cosmic string tension $G\mu \sim 10^{-5}$. Observations rule out any stable cosmic strings of tension $G\mu > 10^{-7}$[6], however. Fortunately, very simple modifications of this setup can avoid this difficulty be ensuring that the strings are unstable. For example, one could have $I_{ac} > 1$, ensuring that there is more than one waterfall field, or alternatively, gauge groups $U(N)$ with $N > 1$. In either case, Π_1 of the vacuum manifold is trivial, and stable cosmic strings do not form.

Note that we have not discussed moduli stabilization in this setup. Instead, we have simply assumed that closed string moduli are stabilized at a scale well above the scale of inflation. A variety of moduli stabilization schemes are now known in Type II string theory. It would be of great interest to understand in detail how moduli can be stabilized in a way consistent with this inflation setup, and in particular with $V_F < V_D$.

4 Hidden Sector Baryogenesis

We will see that the generic presence of mixed anomalies can also affect cosmology. One of the interesting questions about cosmology is the origin of the observed baryon asymmetry. The process which generates this asymmetry is called baryogenesis, and Sakharov showed that the three conditions required for it to occur are B violation, CP violation and a departure from thermal equilibrium[7].

Consider a common scenario in intersecting brane models, wherein the $SU(3)_{qcd}$ gauge group arises as a subgroup of a $U(3)$ gauge group living on a stack of D-branes. The diagonal $U(1)_B$ subgroup has baryon number as a charge. From our previous discussion, we see that a generic feature of these intersecting brane models is that this QCD brane stack will intersect with other hidden sector branes, resulting in non-vectorlike matter charged under $U(1)_B$. If G is a gauge group living on a hidden sector brane with such a topological intersection, the result is a $[U(1)_B G^2]$ mixed anomaly. This leads to a non-trivial divergence in the baryon current:

$$\partial_\mu J_B^\mu \propto Tr[F_G \wedge F_G].$$

This non-vanishing divergence provides precisely the the type of baryon number violation required for baryogenesis[8]. In particular, sphaleron or instanton processes in the hidden G sector which transition between different vacua will result in a shift in the baryon number. In any phenomenologically viable IBM, the gauge group G must either break or confine, in order to avoid the presence of massless exotic fermions charged under $SU(3)_{qcd}$ and G. If the associated phase transition is first order (and accompanied by CP-violation, which is generically possible), then all Sakharov conditions are satisfied and a baryon asymmetry can be generated.

This mechanism of hidden sector baryogenesis seems very reminiscent of electroweak baryogenesis[9], wherein sphalerons in the electroweak sector drive the baryon asymmetry. EWBG is an interesting and well-studied model, partly because it is very concrete and in specific implementations (such as the SM or MSSM) can be analyzed precisely and in detail. In this regard, it is almost too successful; EWBG is ruled out in the SM, and can only fit into a very narrow window of MSSM parameter space ($m_h < 120\,\text{GeV}$, $120\,\text{GeV} < m_{stop} < m_{top}$).

What we see in this intersecting brane model context is that the electroweak gauge group is just one group. One expects several other groups to appear

which also have mixed anomalies with $U(1)_B$, and for a realistic model all of these groups must exhibit some phase transition. Any of them can just as well generate a baryon asymmetry through sphalerons at a symmetry breaking transition. If even one of these hidden sector groups has a first order transition, HSB can work. In this sense, it is a quite robust feature of IBMs.

One might worry that these hidden sectors could break at a scale higher than the electroweak scale, with electroweak sphalerons washing out the generated asymmetry. But in general IBMs, there is a $U(1)_{B-L}$ anomaly as well as a $U(1)_B$ mixed anomaly. Here, $U(1)_L$ is the gauge theory living on the brane where all leptonic strings end. A $[U(1)_L G^2]$ mixed anomaly will arise if this leptonic stack has non-zero topological intersection with the G stack. This is generically the case, and there is no reason for $U(1)_B$ and $U(1)_L$ to have the same intersection numbers with G (unless those branes are parallel, as in a Pati-Salam model). Since the $U(1)_B$ and $U(1)_L$ anomalies will then have different coefficients, the $U(1)_{B-L}$ anomaly will not cancel. Thus, the symmetry breaking transition for G can generally occur at any scale (including high scales), and the $U(1)_{B-L}$ asymmetry ensures that the generated baryon asymmetry cannot be washed out.

Interestingly, hidden sector baryogenesis can arise at the end of the inflationary scenario described in section 3, with the inflationary gauge sector acting as the hidden sector. There will generically be chiral matter charged under both the inflationary sector and $U(1)_B$, contributing to a mixed anomaly which generates a non-trivial divergence of the baryon current. When the waterfall field condenses to end inflation, energy is dumped into the hidden sector through a process called tachyonic preheating[10]. This process will excite long-wavelength modes, including sphalerons which drive baryon violation. This fast process necessarily occurs out of thermal equilibrium and can be accompanied by CP-violation, thus satisfying the Sakharov conditions. Thus, the scale of inflation and the scale of baryogenesis are tied together. This type of baryogenesis was studied in the context of the electroweak group [11]. In that context, however, inflation would have to occur at the electroweak scale, which can be difficult to reconcile with observation. We see that in the context of our inflationary scenario, a higher inflation scale is possible.

5 Conclusions

One of the unique features of string theory is the ability to create unified models of quantum gravity, matter and gauge theory. As such, one would hope that these models would provide insight useful to both cosmology and phenomenology. We have seen that intersecting brane models have several general features which lead to interesting models of cosmology. In a similar vein, one also finds that these general string features have phenomenological applications to dynamical supersymmetry breaking[12] and other signatures at the

LHC[13]. Given the current and upcoming observational data from cosmology and the prospect of new data coming soon from LHC, it is worthwhile to study new physics scenarios which can provide insight relevant to both types of data.

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